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An efficient and cost-effective microchannel plate detector for slow neutron radiography

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ABSTRACT

A novel approach for efficiently imaging objects with slow neutrons in two dimensions is realized. Neutron sensitivity is achieved by use of a boron doped microchannel plate (MCP). The resulting electron avalanche is further amplified with a Z-stack MCP before being sensed by two orthogonally oriented wire planes. Coupling of the wire planes to delay lines efficiently encodes the position information as a time difference. To determine the position resolution, slow neutrons were used to illuminate a Cd-mask placed directly in front of the detector. Peaks in the resulting spectrum exhibited an average peak width of 329 μm FWHM, corresponding to an average intrinsic resolution of 216 μm. The center region of the detector exhibits a significantly better spatial resolution with an intrinsic resolution of <100 μm observed.

1. Introduction

Neutrons are a powerful, non-destructive probe used for imaging in a wide variety of applications [1]. Due to the large penetrating power of neutrons and different absorption cross-sections [2], neutrons are useful for revealing internal structure situated deep within materials. To assess the performance of equipment both prior to and during prolonged use, neutron imaging has been widely utilized to both inspect welds [3] as well as to discern microfractures that compromise the structural integrity of materials [4]. The technique has also been used to advance the understanding of water transport in fuel cells, a key issue impacting fuel cell performance [5–7]. Screening weapons in the nuclear stockpile prior to their disassembly [8] is yet another application of neutron radiography. Detectors that simultaneously provide time-of-flight information in addition to position information enable Bragg-edge imaging which allows identification of microstructural information such as alloy phase distributions, grain size, grain orientation, and strain [9]. The non-destructive nature of neutron radiography makes it well suited to studying art and cultural artifacts [10].

Common characteristics desired in a neutron detector are high spatial resolution, fast time response, and high detection efficiency as these characteristics enable acquisition of high quality neutron images. A traditional approach in slow neutron radiography involves coupling a neutron-sensitive scintillator, such as ^{6}LiF, GADOX (gadolinium oxisulfite), or ZnS:Cu, to a CCD camera. For an optimized scintillator-camera assembly, a spatial resolution of 200 μm can be obtained however with a detection efficiency of only 0.1% [11]. In this approach, although the spatial resolution is reasonable, the time response of the CCD is relatively poor. The high gain and fast temporal response of a MCP detector combined with its sensitivity to photons, ions, or electrons make it the detector of choice for a wide variety of applications. By doping an MCP with ^{10}B the detector can be made sensitive to thermal neutrons with a detection efficiency of 14%–18%. Calculations indicate a theoretical upper limit of 50% for the detection efficiency [12,13]. Using this approach the highest spatial resolution in neutron radiography, ∼15 μm FWHM, has been obtained by coupling a ^{10}B doped MCP to a Medipix2/Timepix CMOS detector [14–16]. This high level of spatial resolution with good efficiency is only achieved for a limited area (28 mm × 28 mm). Moreover, this approach is costly due to the large number of individual charge sensing elements thus restricting its applicability. As many applications favor or even require coverage of a large area, the scalability of any position sensitive neutron detector is a significant issue. Using induced signals coupled to a delay line readout with high speed digitization [17,18] sub-100 μm resolution (FWHM) for a single electron position has been demonstrated [17–21]. To provide a detector with good spatial resolution, efficiency, and the capability of

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tiling large areas, we have investigated applying this approach to slow neutron radiography.

2. Experimental setup

The experimental setup used to detect slow neutrons and to determine the spatial resolution of the MCP-sense wire (MCP-SW) detector is depicted in Fig. 1. The entire assembly shown is housed in a vacuum chamber that is evacuated to a pressure of 5×10^{-7} torr. Slow neutrons were provided by the Low Energy Neutron Source (LENS) at Indiana University, Bloomington [22–25]. This facility generates neutrons using a pulsed, high-intensity proton beam and the ^{9}Be(p,n) reaction. LENS was operated at a frequency of 20 Hz. The resulting neutrons are thermalized by a polyethylene and solid methane moderator at ∼6.5 K before being delivered to the experimental station at a flux of 2.7–5×10^4 neutrons s^{-1} cm^{-2}. As evident in Fig. 1, neutrons are first incident on a cadmium mask. Slow and thermal neutrons that pass through slits in the mask are captured by a ^{10}B doped MCP (MCP-B). The MCP-B was a standard Nova MCP with 25 mm diameter active area [26]. The 8 μm diameter microchannels had a center-to-center spacing of 10 μm and an l/d ratio of 80:1 [26]. The ^{11}B produced following capture of the thermal neutron decays into an α-particle (1.777 MeV) and a ^{7}Li nucleus (1.014 MeV). These charged products initiate an electron avalanche in the MCP-B detector. This avalanche is subsequently amplified in a MCP Z-stack detector (MCP-Z), which is a standard Photonis MCP (APD 3 40/12/10/12 D 60:1) with 10 μm diameter microchannels [27]. The electron cloud emanating from the MCP stack is sensed by the two orthogonally oriented wire planes before being collected on an anode. The signal induced on the sense wire planes is inherently bipolar. This characteristic bipolar signal enables distinguishing small amplitude signals from noise. These wire planes are both mounted on a precisely machined part to define their relative orientation. In order to efficiently readout the signals from each wire plane, wires in each plane were coupled to a delay line. Each delay line, consisting of a 7771 mm trace on a high-quality printed circuit board, resulted in a delay of ∼1.14 ns between adjacent wires [20]. Examining the time difference between the arrival of the signal at the two ends of the delay line provides a measure of the electron cloud position. Thus, spatial information is encoded as a time difference. This time difference can be accurately determined by digitizing and analyzing the sense wire signals. This approach benefits from recent developments in high speed digitization where digitizers with sampling frequencies greater than 1 GS/s are now routinely available at modest cost. Implementation of the delay line readout makes the detector cost-effective and therefore scalable [21]. Although the total neutron dose such a detector can withstand before its performance is degraded is undetermined, boron-doped MCPs have been successfully used in imaging measurements at Paul Scherrer Institute's ICON facility with a flux of 8×10^6 n s^{-1} cm^{-2} [16].

The optimized operating conditions for the detector required the entrance of the MCP-B to be held at ground, while the MCP-B rear surface was biased to +1242 V. The voltages on the entrance and exit of the MCP-Z were +1373 V and +3900 V, respectively. To accelerate the electron cloud following the MCP-Z, a potential of +3915 V and +3930 V was applied to the wire planes. Collection of the electrons at the anode was ensured by biasing it to +4030 V. As the high voltage power supply (HVPS) can constitute a significant noise source, the MCP-B, MCP-Z and SW were biased using a low-noise, HVPS (ISEG NHQ224M) and the anode was biased using a HVPS (ISEG NHQ226L).

The signals arriving at either end of the delay line are designated Y_{Up} and Y_{Down} for the Y-dimension and X_{Left} and X_{Right} for the X-dimension. These four position signals along with the MCP and anode signals were fed through the vacuum interface using high quality SMA feedthroughs. The integrity of the signals was preserved by minimizing the distance from the vacuum chamber to the detector electronics and using high quality cable (RG316). The first element of the electronics was a custom built low-noise amplifier (gain = 30, bandwidth = 150 MHz) which was used to amplify each of the position signals prior to their digitization.

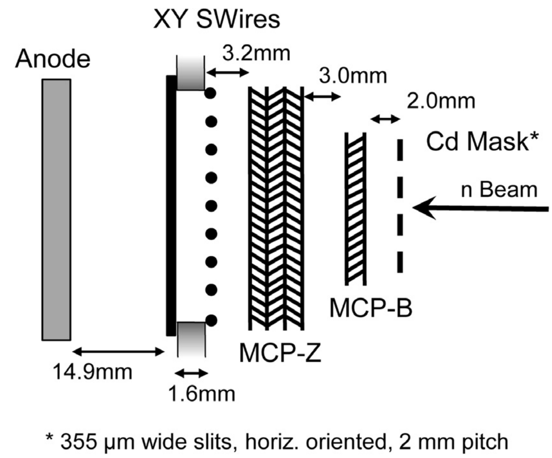

Fig. 1. Experimental setup used to test the spatial resolution of the MCP-SW detector when illuminated with thermal neutrons.

3. Data acquisition system

In order to effectively digitize the signals from the MCP-SW detector, a data acquisition (DAQ) system was constructed as shown in Fig. 2. The system developed was based upon the PCIe standard in order to allow for a high data transfer rate of the digitized signals. The key element in the DAQ is the Alazar ATS9373 digitizer. This 12-bit waveform digitizer has an analog bandwidth of 2 GHz and can operate either as a single channel at 4 GS/s or as two independent channels at 2 GS/s. In all the reported measurements, the digitizer is operated in the latter mode. This digitizer is capable of a data transfer rate of 6.8 GB/s. Data are recorded on a solid state SATA 3 drive capable of a sustained write rate ∼500 MB/s. This recording capability is the limiting step in the DAQ and enables a neutron detection rate of 200k cps. In the DAQ system, two ATS9373 digitizers are used to enable digitization of the Y_{Up}, Y_{Down}, X_{Left}, and X_{Right} signals. To make use of the pulsed neutron beam at LENS, a time-to-digital converter (TDC) was developed. The TDC is realized on a Xilinx AC701 development kit. The 125 MHz clock provides a limit to the time resolution of 8 ns, which is sufficient for the selection of slow neutrons. To test the asynchronous response of the DAQ, an uncollimated ^{241}Am α-source was placed directly in front of the masked 2D MCP-SW detector. The digitizers were triggered using the anode signal after its amplification by an RF Bay LNA-530 amplifier (gain = 30 dB, bandwidth = 500 MHz). With this setup we were able to record data at a count rate of 8k cps using a 10 μCi α-source. The 2D position spectrum anticipated for the masked detector was observed indicating that synchronization of the ATS9373 boards is maintained.

4. Measuring the spatial resolution of the MCP-SW detector

Obtaining position information from the detector requires ascertaining the difference in the time-of-arrival of the signal at the two ends of the delay line. This is accomplished by processing each induced signal's digitized waveform through a software constant fraction discriminator (CFD) in the offline analysis. The fraction chosen was 50% of the bipolar signal's positive lobe. A CFD was chosen to eliminate the walk associated with more commonly used leading edge discrimination.

To assess the spatial resolution of the detector for neutrons, a Cd mask (0.5 mm thick) is mounted 2 mm in front of the MCP active area. The mask provides an effective block (transmission ∼0.3%) for 25 meV neutrons. The precision mask, fabricated by electrical discharge machining (EDM), has 7 slits each with a width of ∼355 μm and a center-to-center spacing of 2.0 mm. As accurate knowledge of the slit widths is necessary to extract the intrinsic resolution from the measured position spectrum, the mask was examined using a Leica M205FA Stereo